DEVELOPMENT OF MULTI-MEGA WATT NEGATIVE ION SOURCES AND ACCELERATORS FOR NEUTRAL BEAM INJECTORS

M.Hanada, N.Akino, N.Ebisawa, Y.Fujiwara, A.Honda, T.Itoh, K.Kawai, M.Kazawa, M.Kuriyama, K.Miyamoto, K.Mogaki, T.Ohga, Y.Okumura, H.Oohara, K.Oomori, K.Usui, and K.Watanabe
Japan Atomic Energy Research Institute,
801-1 Mukohyama, Naka-machi, Naka-gun, Ibaraki-ken 311-0193, Japan

Abstract

High energy and high power negative ion sources and accelerators have been developed for neutral beam (NB) injectors of future fusion machines such as International Thermonuclear Experimental Reactor (ITER). Using a 5-stage electrostatic accelerator, negative ion beam has been successfully accelerated up to the energy of 1 MeV, which is the required energy for ITER. Powerful negative ion beams of 18.5 A, 360 keV H^- and 14.3 A, 380 keV D^- have been produced with a high arc efficiency of 0.11 A/kW at a low source pressure of 0.15 Pa in JT-60 negative ion sources, and neutral beams of 5.2 MW have been injected into the plasma. Continuous operation of a Cs-seeded negative ion source has also been demonstrated for 140 hours, which is equivalent to the half year operation in the ITER-NB system.

1. INTRODUCTION

Negative-ion-based neutral beam (N-NB) injection is one of the promising candidates to heat dense plasma and to drive plasma current in future fusion machines. In ITER, for example, 50 MW, 1 MeV D^0 beams are to be injected to the plasma using three injectors. [1] The key component in the N-NB system is a beam source consisting of a negative ion source and an accelerator. The beam source has to produce a 40A (200 A/m^2), 1 MeV D^- beam for 1000 s for the N-NB system in ITER. To achieve these requirements, two major R&D's have been carried out at Japan Atomic Energy Research Institute (JAERI).

One is the development of a high energy negative ion accelerator. A Multi-Aperture, Multi-Grid (MAMuG) electrostatic accelerator is selected as the reference design in the ITER-NB system to accelerate the high current negative ion beams up to 1 MeV. To establish the technology of the MAMuG accelerator, a five-stage electrostatic accelerator was designed and has been tested at MeV Test Facility (MTF) [2]. Voltage holding capability and beam optics of the negative ion beam are studied to achieve the stable acceleration of negative ion beam up to 1 MeV.

The other is the development of the JT-60 N-NB system that is the first N-NB injector in the world. The system is designed to inject 500 keV, 10 MW D^0 beams to the plasma. [3] The first injection started in March 1996, and the injection power increased step by step to reach 370 keV, 5.2 MW in 1998.

In parallel with two major developments, a long pulse operation of the Cs-seeded negative ion source has been demonstrated to quantify the negative ion yield during the long pulse operation and to estimate the maintenance frequency of the ion source. In the present paper, the latest experimental results obtained in these R&D's are described.

2. DEVELOPMENT OF A 1 MEV, 1A NEGATIVE ION ACCELERATOR

Figure 1-a shows a photograph of the 1 MeV beam source. The negative ions are produced in a semi-cylindrical plasma generator called "KAMABOKO" source that can produce negative ions efficiently at a low operating pressure. The negative ions are separated from electrons in the extractor and are accelerated in a five stage MAMuG accelerator. The same acceleration voltage of 200 kV is applied in each acceleration stage. To compensate the beam expansion due to space charge of the high current density beam, electric lenses are formed by strengthening electric field, i.e., by shortening the gap lengths in the downstream stages. These configurations of the accelerator are the same as those of the reference design in the ITER-NB system.

FIG.1-a A 1MeV beam source

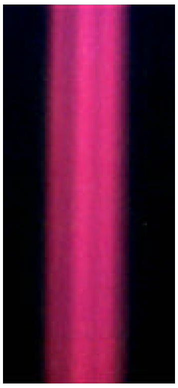

FIG.1-b 400 keVH^- beamlets from 3x3 apertures in the 1 MeV beam source

As reported in ref [4], the highest energy had been limited 700-800 keV because of voltage holding capability of the accelerator column made of FRP (Fiber Reinforced Plastic). It turned out that the insulator was damaged by glow-like discharge that was initiated by micro-discharge and maintained by a large amount of outgassing from the FRP insulator. To avoid the damage of the insulator, two modifications have been taken. Namely, the gas flow conductance of the support flanges was increased for the efficient pumping of the gas, and protection resistors for intermediate acceleration stages were increased to reduce the surge current. Figure 2 shows the characteristic of voltage holding capability after the modification. The withstand voltage increased quickly up to 800 kV and then tended to saturate. By using the region of the higher withstand voltage, i.e., by increasing the pressure near the insulator, the withstand voltage was increased to 950 kV at a typical source operating pressure of 0.4 Pa. After additional 6-hour conditioning, the withstand voltage reached 1 MV. Figure 3 shows the V-I characteristic of the accelerator after the total conditioning time of 12 hours. The resistance calculated from the graph was in agreement with that of cooling water. This indicates that the glow-like discharges can be sufficiently suppressed by the modifications described above. Followed by the conditioning, a 25 mA (drain current of power supply) H^- beam was successfully accelerated up to 1 MeV for 1 s through central 9 apertures of 14mm in diameter. No degradation of the voltage holding capability due to the beam acceleration has been observed.

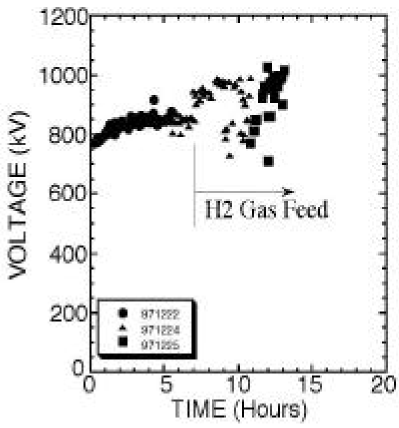

Fig.2 Voltage holding capability

To investigate the beam optics in the 5-stage accelerator, the extraction voltage (Vext) and the acceleration voltage (Vacc) were varied simultaneously while arc power was fixed at 9.5 kW and the voltage ratio of Vext/Vacc at 1/143, which gives the lowest beam divergence. In this operation, an ion extraction sheath was varied while the negative ion production and the electric lenes were kept to be constant. The accelerated beam current is plotted as a function of Vext in Fig.4. The beam current increases in proportional to $(Vext)^3$ in the region of the low extraction voltage, where some of the negative ions were intercepted directly by the extractor (region I). The beam current increases in proportional to $(Vext)^{1.5}$ at the higher extraction voltages, where the ion extraction sheath was formed properly in the source, so that all the extracted negative ions passed through the grids in the extractor and accelerated in the following 5 acceleration gaps (region II). In this region, the beam current was limited by space charge, i.e., Child-Langmuir law. Then the beam current tends to saturate (region III). In the region III, the beam current was limited by the saturation of the negative ion density in the negative ion source. A minimum divergence angle of less than 5 mrad was obtained at the inflection point from the region II to the region III, i.e., at Vext=2.8 keV, where 3 distinguished beamlets were observed as shown in Fig.1-b. The beam optics quantitatively agrees with the theoretical

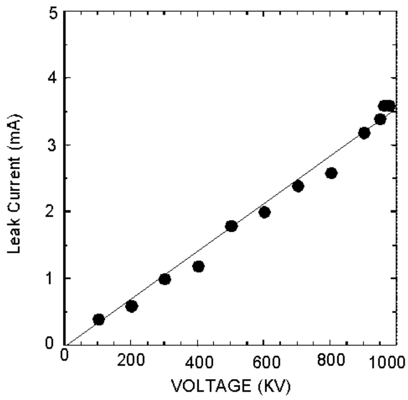

Fig.3 V-I characteristics

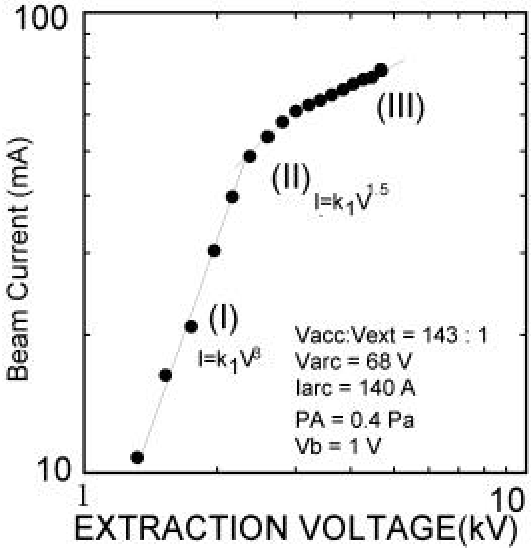

Fig.4 Beam current as a function of extraction voltage in a 1 MeV beam source

prediction. Extrapolating from the present experimental result, it is predicted that a low divergence angle can be obtained for the 1 MeV, 200A/m^2 D^- beams designed for ITER.

3. DEVELOPMENT OF THE JT-60 N-NB SYSTEM

A high current beam source has been developed for the JT-60 N-NB system. The beam source consists of a Cs-seeded volume negative ion source called "KAMABOKO" source and a three-stage MAMuG accelerator that has the same design concept as the beam source for ITER-NB system. Figure 5 shows the negative ion beam currents measured by water calorimetry as a function of the arc power. The beam energies were 360-380 keV. The beam current increases linearly with the arc power and reaches 18.5A H^- at 160 kW and 13.8 A D^- at 150 kW. The arc efficiencies are as high as 0.11 A/kW for the H^- production and 0.09A/kW for the D^- production. The most significant feature of the source is that the source can be operated at an extremely low operating gas pressure. The optimum gas pressure giving the highest negative ion yield was as low as 0.15 Pa. This allows us to reduce the stripping loss of negative ions in the accelerator to less than 10%, resulting in a high acceleration efficiency of more than 80%. Both of the arc efficiency and the operating source pressure were superior to the design values extrapolated from the smaller negative ion sources. This is due that the plasma confinement is improved by enlarging the ion source. Considering that the ITER source is twice larger than the JT-60 negative ion source, further improvement of the negative ion production is expected.

The accelerated negative ions are neutralized in a long gas cell of 11 m. It is measured that the neutralization efficiency of the negative ions is 60% over the wide energy range of 100-400 keV/nucleon. This agrees well with the calculation result using cross-section data. Neutral beams converted from the negative ion beams are injected to the plasma through a long drift duct of 4 m. At the beginning of the injection, the beam power and beam pulse length were restricted to be a low level because of high re-ionization loss of the drift duct. By repeating beam injections with short pulse duration of 0.5 s, the pressure inside the duct was reduced, resulting in the reduction of the re-ionization loss. It takes 40 pulses or total pulse length of 20 s to reduce the re-ionization loss to 1.5-2.0 % for 350 keV D^o and H^o beams. The re-ionization loss after the conditioning is nearly equal to the design values calculated theoretically. After the reduction of the re-ionization loss, the injection efficiency in the beamline including neutralization efficiency, beam transmission and re-ionization was 51%.

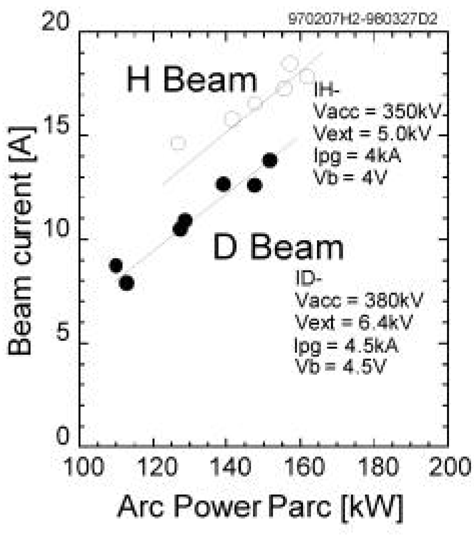

Fig.5 Beam current as a function of arc power in the JT-60 negative ion source

Figure 6 shows the progress of neutral beam power injected to the plasma. The injected power increased step by step and reached 5.2 MW D^0 at 370 keV. The beam pulse length has also been increased to around 2 s.

4. LONG PULSE OPERATION OF A NEGATIVE ION SOURCE

The pulse duration required for the ITER-NB system is more than 1000 s. It is assumed that NB system is

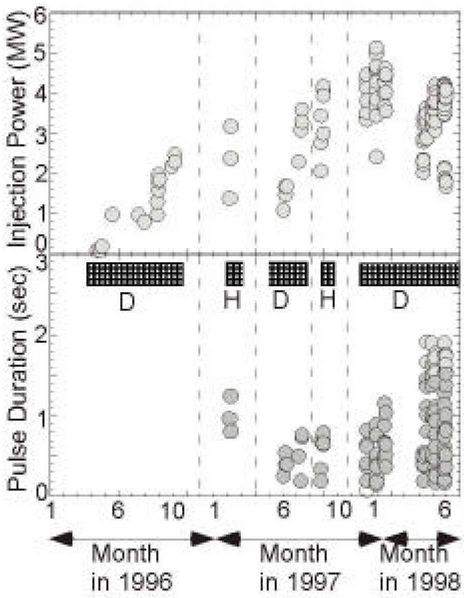

Fig.6 Progress of neutral beam power injected to the plasma in JT-60U

operated for up to 1000 pulses a year, and regular maintenance is planned every half year. This means that the beam source has to be operated at least for half year, namely for 500 pulses of 1000 s duration without any maintenance.

One of the critical issues in the long pulse operation is a cesium diffusion from the source to the accelerator, resulting in degradation of the negative ion yield and the voltage holding capability of the accelerator. To quantify the cesium flowing to the accelerator, a small Cs-seeded negative ion source having an extraction area of 11cm x 12cm [4] has been operated continuously for 140 hours, which corresponds to half year operation in the ITER-NB system. By injecting 500mg of cesium to the ion source, a 0.2-0.3 A, 30 keV H^- ion beam has been produced for 140 hours. No degradation of the beam current and voltage holding capability of the accelerator was observed. It turned out that the amount of cesium flowing out to the accelerator was as small as 40 mg, i.e., 8% of the injected cesium. More than 90% of the injected cesium is confined in the plasma generator. This is because the cesium has a big cross section for ionization and the cesium positive ions are confined electrostatically in the source plasma.

The negative ion yield is a strong function of the temperature of a plasma grid [5]. It is necessary to keep the temperature at 250-300 ^{o}C during the long pulse operation. A new plasma grid having a thermal bridge around the grid flame has been developed and tested. The temperature was kept at 300 ^{o}C at an arc discharge power of 18 kW, where a high current H beam of 850 mA (220A/m^2) was successfully produced in the long pulse operation.

5.SUMMARY

A high energy 1 MeV H^- beam and powerful negative ion beams of 18.5A, 360keV have been produced by using a Cs-seeded negative ion source and a multi-stage electrostatic accelerator. It was also demonstrated that the Cs-seeded negative ion source can be operated stably for 140 hours. These results give confidence that 40A, 1MeV beam source for ITER-NB system is feasible.

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